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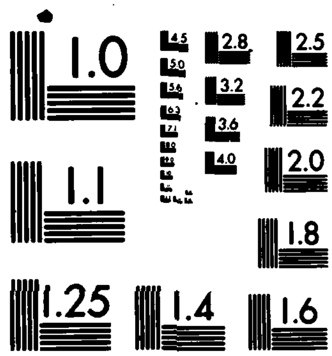

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ON PARAMETERS OF A SUPERSONIC COMBUSTION CHAMBER WITH ORGANIZATION OF COMBUSTION AT THE FLAME FRONT

by

E.L. Solokhin, V.A. Mironenko, V.I. Ivanov

FOREIGN TECHNOLOGY DIVISION

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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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ON PARAMETERS OF A SUPERSONIC COMBUSTION CHAMBER WITH ORGANIZATION OF COMBUSTION AT THE FLAME FRONT

E. L. Solokhin, V. A. Mironenko, V. I. Ivanov

Notation: P, T are static pressure and temperature; P^*, T^* are stagnation pressure and temperature; M is the velocity coefficient; J is the total flow momentum in the section being examined; F is the area; $P_{тр}$ is the force of friction; G is the consumption by weight; k is the adiabatic index; C_p is the thermal capacity; Q is the heat given off during chemical reaction; A is 1/427-heat equivalent of mechanical work; U is velocity; g is the acceleration of gravity; i^* is the total enthalpy; α is the angle of inclination of the flame front with respect to the velocity vector of the fuel mixture; u_T is the turbulent velocity of flame propagation; ρ is density; C_f is the drag coefficient; σ is the coefficient of preservation of total pressure; ζ is the friction coefficient; Π is the perimeter; b is the width of the combustion chamber; $Y_в$ is the halfheight of the combustion chamber at intake; $Y_ф$ is the ordinate of the flame front; $Y_к$ is the current halfheight of the combustion chamber; Hu is the lower calorific value of the fuel; C_T is the fuel weight concentration; K_F is a coefficient; a is the velocity of sound; $\alpha_н$ is the excess air ratio at the intake in the combustion chamber; $\alpha_к$ is the local value of the excess air ratio; L_0 is the stoichiometric mixture ratio; $u_н$ is the normal velocity of flame propagation; A_s (2.4) is an experimental coefficient; U is the pulsation component of velocity; P^0, T_0 are the pressure and temperature of the mixture for the prescribed value α_e for which the normal velocity of flame propagation is equal to $u_{0н}$ (experimental values); ε_t is the degree of turbulence; R is the gas constant; L_θ is the distance to the flame line; L_ϕ is the length of the flame; x, y are coordinates; A, Б, B are typical longitudinal sections of the combustion chamber; "CM" is mixture; "п" denotes reaction products; "B" intake into the combustion chamber.

In some engineering problems, it is necessary to burn fuel in the combustion chamber with supersonic flow. As a rule, the scheme of organization of the process in such a chamber presupposes a separate accompanying feed of fuel and oxidant in which combustion of fuel takes place in a diffusion flame front. In this article we give theoretical results of investigation of a supersonic combustion chamber in which combustion of the fuel mixture takes place in an oblique flame front stabilized by an external source (analogous to the subsonic combustion chambers of ramjets). The possibility of the existence of (such previous) an oblique flame front in a supersonic flow of fuel mixture was proved experimentally in [5].

Diagram of the Combustion Chamber and a Model of the Process

A diagram of the combustion chamber is shown in Fig. 1. The following organization of the combustion process in the chamber is proposed. A supersonic flow of fuel-air mixture arrives at the combustion chamber intake (section A-A). Fuel gas is introduced into the same section A-A which has a static temperature higher than the static temperature of the main flow. The fuel gas, on mixing with the fuel-air mixture, ignites the latter at a certain distance from section A-A. The ignition point or the flame stabilization line (in section B-B) is adopted as a constantly acting ignition source, which ignites the turbulent oblique flame front. The fuel mixture, on passing through the flame front, undergoes combustion. The method of obtaining a constantly acting ignition source may be a different one, for instance, a pilot flame in the bay of the chamber wall. Conditions for obtaining an ignition source and conditions for it to be stable are not examined here.

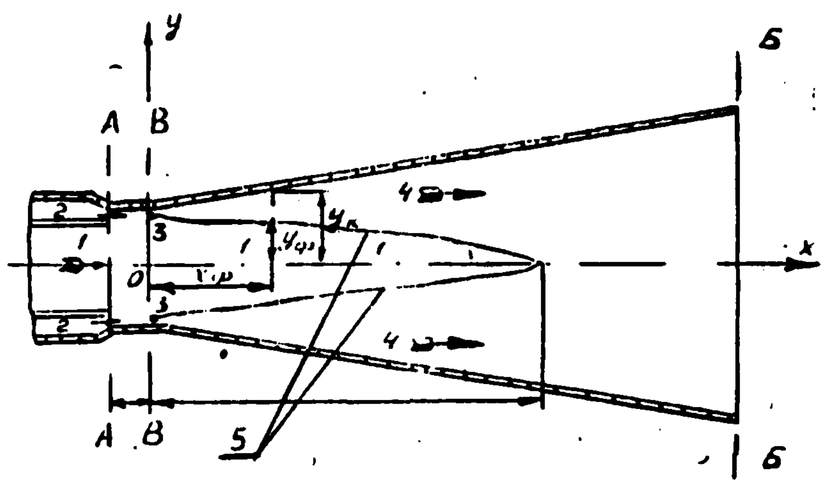

Fig. 1. Combustion chamber diagram: 1 - fuel-air mixture; 2 - fuel gas; 3 - projection of the flame stabilization line; 4 - reaction products; 5 - flame front.

A System of Equations for the Process in the Combustion Chamber

In putting together a system of equations describing the process in a supersonic combustion chamber, the following assumptions are made:

1. The flame front is infinitely thin.

2. The static pressure in any cross section of the chamber is constant.

3. The boundary layer of the chamber wall is partially accounted for by the force of friction.

4. Dissociation of reaction products is not taken into account.

5. The field of parameters of the gas flow in a cross section at the chamber intake are uniform.

The adopted assumptions sharply idealize the real process in the combustion chamber. Nevertheless, examination of the problem in this formulation can give an idea as to the order of the major variables characterizing the combustion chamber on the whole: the necessary length, the coefficient of preservation of full pressure, the velocity coefficient and other parameters on the outlet of the chamber.

All the calculations given below are relative to a combustion chamber of rectangular section with parallel side walls.

The problem is to find the ordinate of the flame front Y_{ϕ} and the parameters of the reaction products and fuel-air mixture along the length of the combustion chamber. As the parameters to be determined along the length of the combustion chamber we have chosen: the static pressure P, which for the reaction products and the fuel mixture in the examined section is the same, the velocity coefficients M_{n} and M_{cm}, the velocities of sound a_{n} and a_{cm}. The quantities are sufficient for determining any other parameters of the reaction products and fuel mixture.

To solve the problem we use the following equations, written out for an arbitrary section of the chamber.

1. The equation for preservation of total momentum taking into account friction on the chamber wall

$$J_{н}+J_{см}-J_{в}=\int_{F_{в}}^{F_{Б}}PdF-P_{тр} \quad ; \tag{1}$$

2. The consumption equation

$$G_{н}+G_{см}=G_{в} \tag{2}$$

3. The adiabatic equation for the fresh fuel mixture

$$\frac{T_{см}}{T_{в}}=\left(\frac{P}{P_{в}}\right)^{\frac{K_{см}-1}{K_{см}}} \tag{3}$$

4. The energy equation

$$G_{в}i^{*}_{в}=G_{н}i^{*}_{н}+G_{см}i^{*}_{см}-Q_{в} \tag{4}$$

5. The enthalpy equation for the fresh fuel mixture

$$i^{*}_{в}=i^{*}_{см}. \tag{5}$$

6. The equation determining the position of the flame front in the flow

$$\sin\alpha=\frac{u_{т}}{U_{см}} \tag{6}$$

Let us rewrite equations (1)-(6) in the parameters selected as unknowns, having first expressed the values of $U_{см}$ and $u_{т}$ in terms of them.

The force of friction on the segment from Ø to X is determined by the equality

$$P_{mp} = \int_0^x C_f \frac{\rho_n U_n^2}{2} \Pi dx. \tag{7}$$

If one takes into account that

$$C_f = \frac{\zeta}{4}, \tag{8}$$

$$\Pi = \theta + 2y_\kappa, \tag{9}$$

then equation (7) can be put in the form

$$P_{mp} = \frac{\zeta K_n}{8} \int_0^x P M_n^2 (\theta + 2\bar{y}_\kappa) dx \tag{1Ø}$$

The quantity of heat Q given off on the section from Ø to X

$$Q = \theta H u \int_{y_\phi}^{y_\theta} \rho_{c.m} U_{c.m} C_T \, dy \tag{11}$$

or

$$Q = \theta H u K_{c.m} g \int_{y_\phi}^{y_\theta} \frac{P M_{c.m}}{u_{c.m}} C_T \, dy. \tag{12}$$

The fuel concentration in the mixture

$$C_T = \frac{a_m}{a_m L_0 + 1} \quad \text{for} \quad a_m < 1 \tag{13}$$

and

$$C_T = \frac{1}{a_m L_0 + 1} \quad \text{for} \quad a_m > 1. \tag{14}$$

Since there is a limited amount of data on the velocity of flame propagation in supersonic flows, we use the equation for u_T

proposed in [2]:

$$u_T = u_H \left[\Theta + \frac{4.5 \frac{U'_{cM}}{u_H}}{\sqrt{\ln\left(1+\frac{U'_{cM}}{u_H}\right)}} \right], \tag{15}$$

where the normal velocity of the flame propagation u_H is calculated by the formula derived according to the data of [3],

$$u_H = u_{H0} \left(\frac{T_{cM}}{T_0}\right)^2 \left(\frac{P}{P_0}\right)^{-0.35} . \tag{16}$$

In equation (15) the relative heating up θ is equal to

$$\Theta = \frac{T_n}{T_{cM}} , \tag{17}$$

while the pulsation component of the mixture's velocity is

$$U_{cM}' = \varepsilon_t U_{cM} . \tag{18}$$

It should be noted that the choice of the form of the equation for u_T in this statement of the problem is not really important. The important thing is that it makes it possible to take into account the influence on u_T of the greatest number of physical parameters of the fuel mixture while not contradicting the experimental data on the velocity of flame propagation in supersonic flow available in the most up-to-date literature. For comparing the numerical values of u_T obtained from (15) with the numerical values given in [4], we made the appropriate calculations. The results are shown on Fig. 2, where we see that in the region of lean mixtures for turbulence degree 1% the agreement of the calculated and experimental values of u_T is rather good.

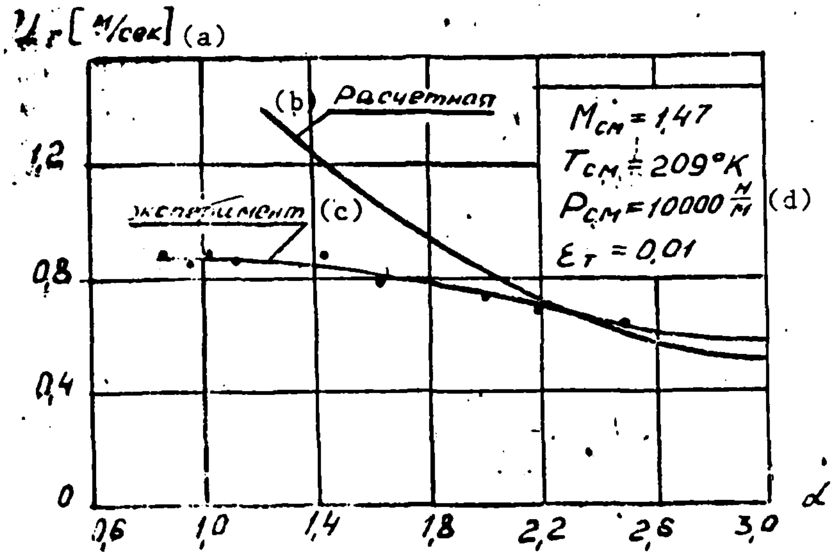

Fig. 2. Dependence of turbulent velocity of flame propagation in a supersonic flow.
Key: (a) m/sec; (b) Calculated; (c) Experiment; (d) N/m.

Other equations that we used in calculations of u_T (not given here) did not affect the final results qualitatively, and the quantitative differences were minor*.

So far, there have been few studies made to clear up the level of intensity of turbulence in high-temperature supersonic flows. In the calculations, one takes $\varepsilon=0.01$, which agrees with the data derived by Baranova in experiments with cold supersonic flows with M=2.5 [5].

*Similar results are obtained if one takes the velocity of flame propagation for different zones of the flame front (the forward, middle and trailing zone or for the maximum-section zone).

One has gotten roughly the same level of intensity of turbulence in experiments carried out under the direction of Tyul'panov. Bearing in mind that

$$\frac{dy_\phi}{dx} = \mathrm{tg}\arcsin\alpha, \tag{19}$$

in final form equation (6) can be written as follows:

$$\frac{dy_\phi}{dx} = \mathrm{tg}\arcsin \frac{u_{no}}{a_{c.м} M_{c.м}} \left(\frac{T_{c.м}}{T_0}\right)^2 \left(\frac{P}{P_0}\right)^{-0.35} \times$$
$$\times \left\{ \frac{\vartheta_n^{\,2} K_{c.м} R_{c.м}}{a_{c.м}^2 K_n R_n} + \frac{2{,}4\,\frac{s_1 a_{c.м} M_{c.м}}{u_{no}} \left(\frac{T_0}{T_{c.м}}\right)^2 \left(\frac{P_0}{P}\right)^{-0.35}}{\sqrt{ln\left[1+\frac{s_1 a_{c.м} M_{c.м}}{u_{no}} \left(\frac{T_0}{T_{c.м}}\right)^2 \left(\frac{P_0}{P}\right)^{-0.35}\right]}} \right\}. \tag{20}$$

Accordingly, equtions (1)-(5) as functions of the unknowns can be put in the following forms:

$$\theta y_\theta P_\theta (1+K_{c.м} M_\theta^{\,2}) = \theta P \Big[y_\phi (1+K_{c.м} M^2_{c.м}) + (y_к - y_\phi) \times$$
$$\times (1+K_n M_n^{\,2}) \Big] + \frac{\vartheta K_n}{8} \int_0^x P M_n^2 (\theta + 2y_к) dx - \int_{F_B}^{F_Б} P dF \tag{21}$$

$$P_\theta K_{c.м} \frac{M_\theta}{a_\theta} y_\theta = P \left[y_\phi \frac{K_{c.м} M_{c.м}}{a_{c.м}} + (y_к - y_\phi) \frac{K_n M_n}{a_n} \right]; \tag{22}$$

$$a_{c.м}^2 = a_\theta^{\,2} \left(\frac{P}{P_\theta}\right)^{\frac{K_{c.м}-1}{K_{c.м}}}; \tag{23}$$

$$P_\theta K_{c.м} \frac{M_\theta}{a_\theta} y_\theta C_{p\theta} T_\theta^{\,*} = K_{c.м} \cdot g P M_{c.м} a_{c.м} \times$$
$$\times \left(\frac{C_{pc.м}}{K_{c.м}\, g\, R_{c.м}} + \frac{A}{2g} M_{c.м}^{\,2} \right) y_\phi + K_n g P M_n a_n \times$$
$$\times \left(\frac{C_{pc.м}}{K_1\, g\, R_n} + \frac{A}{2g} M_n^{\,2} \right) (y_к - y_\phi) - K_{c.м} g H u \times \tag{24}$$
$$\times \int_{y_\phi}^{y_\theta} \frac{P M_{c.м}}{a_{c.м}} C_1 dy;$$

$$C_{p0} T_0{}^* = a_{c\text{м}} \left(\frac{C_{pc\text{м}}}{K_{c\text{м}g} R_{c\text{м}}} + \frac{A}{2g} M_{c\text{м}}{}^2 \right) \quad (25)$$

Thus, to determine the 6 unknowns (Y_ϕ, P, M_n, $M_{c\text{м}}$, a_n, $a_{c\text{м}}$) along the length of the combustion chamber, one has the six equations (2Ø)-(25).

Results of Numerical Solution of the Derived System of Equations

The system of equations was solved on a digital BESM-2M series computer. The goal of the solution was to derive the distribution of the parameters along the length of the combustion chamber, to determine the length and position of the flame jet, to clarify the special features of the flow in the chamber depending on the physical flow parameters at the chamber intake, the chamber geometry, the kind of fuel, etc.

The chamber chosen for study is symmetric with respect to the plane passing through the x-axis perpendicular to the y-axis (Fig. 1) with dimensions: height at inlet 2y=Ø.Ø5 m, width at inlet σ=Ø.1 m, the law of variation of chamber area along the length is given by the equation

$$F = 2\sigma (y_0 + K_F x) \quad (26)$$

Some obtained results are shown on Figs. 3-8, from which the following inferences may be drawn:

1. To obtain short flame jets, it is necessary to use fuels having high velocities of flame propagation (for example, hydrogen + air). We see from Fig. 7 that the flame jet length for a kerosene-air mixture is 4-5 times longer than for a hydrogen-air mixture.

2. The flame jet length, and consequently also the length of the combustion chamber for broad ranges of variation of the physical parameters at the chamber inlet, are not long and of the same order as for subsonic combustion chambers (see Figs. 3, 4, 5, 6, on which the dependence are given of the flame jet length on the number M, the stagnation temperature, the excess air ratio, the degree of expansion of the chamber and the inlet pressure ino the combustion chamber).

3. To burn the greatest amount of high-calory fuel (for $\alpha_g=1$) without choking the chamber, it is necessary to make it expansible (see Fig. 6). And the degree of expansibility (which corresponds to the coefficient K_F) must be the greater the smaller the number M at the chamber intake. From Fig. 6 we also see that the degree of combustion chamber expansion barely influences the flame jet length.

4. The greatest influence on the flame jet length turns out to be the excess air ratio α (see Fig. 5). The stagnation temperature T_{1*} and the static pressure p at the chamber intake are of less influence than α (see Figs. 3, 4).

5. Calculations have shown that for appropriate combinations of the flow parameters at the chamber intake, the chamber geometry and the kind of fuel, one of the following two typical flow regimes results:

a) $M_u > 1, \quad M_{cm} > 1,$

b) $M_u < 1, \quad M_{cm} < 1,$

i.e., in a section of the combustion chamber there can simultaneously exist both supersonic and subsonic regions of flow

(Fig. 8). It is characteristic that the switchover from one regime of flow to another under variation of any parameter is saltiform.

In conclusion, note that the presented theory of the process in a supersonic combustion chamber and the numerical results need to be checked experimentally and sharpened, since not very much is now known about the values of some of the basic parameters (ε_T, u_T) for supersonic flows.

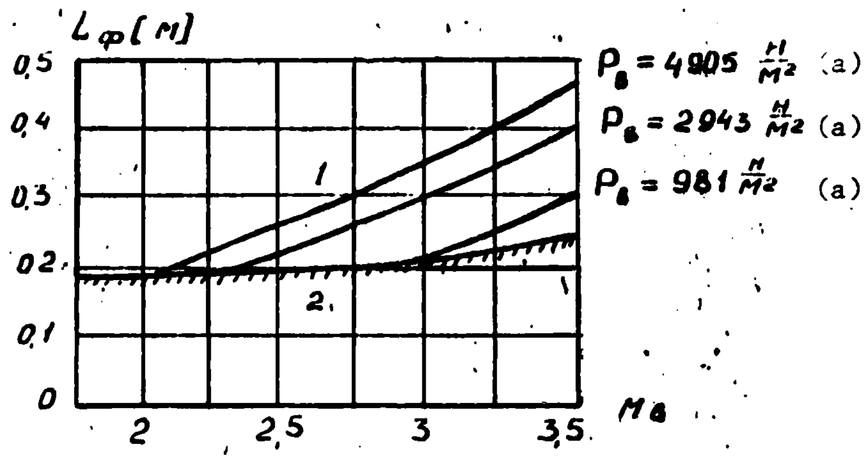

Fig. 3. Dependence of flame jet length on the number M and pressure P . Mixture H_2 + air, $\alpha_g = 1$, $T_g^* = 2000°K$, $\varepsilon_T = 0.1$, $K_F = 0.3$.
Key: (a) N/m^2.

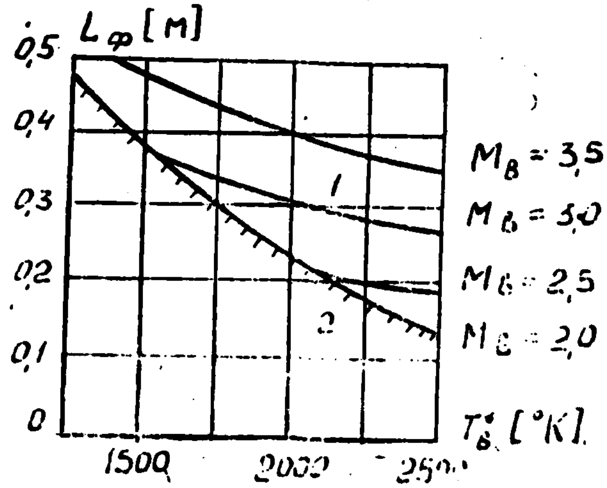

Fig. 4. Dependence of flame jet length on temperature T_θ^* and number M_θ. Mixture H_2 + air, $\alpha_\theta=1$, P_θ =2943 N/m², ε_T=0.01, K_r=0.3; 1 - region of stall-free flow; 2 - region of choking.

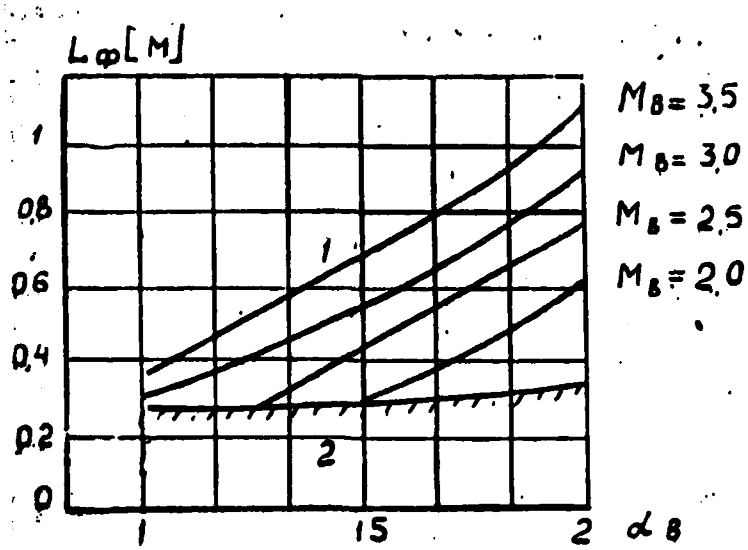

Fig. 5. Dependence of flame jet length on α_θ and M_θ. Mixture H_2 + air, T_θ^*=2000°K. P_θ=2943 N/m², α_θ=0.01, K_r=0.2, 1 - region of stall-free flow; 2 - region of choking.

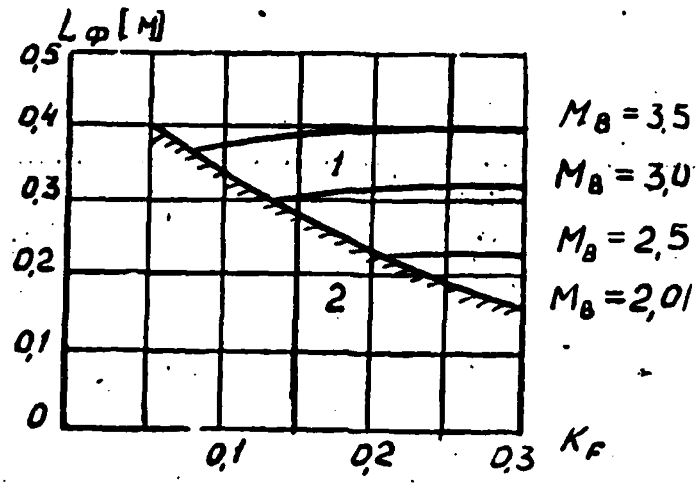

Fig. 6. Dependence of flame jet length on K_F and M . The mixture H_2 + air, $T_B^* = 2500°K$, $P_B = 4905\ N/m^2$, $\alpha_B = 1$, $\varepsilon_T = 0.01$, 1 - region of stall-free flow; 2 - region of choking.

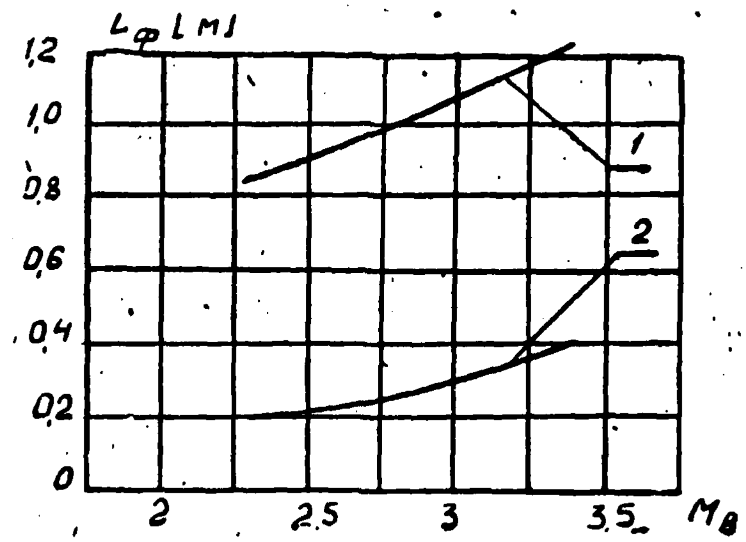

Fig. 7. Dependence of flame jet length on M for different fuel mixtures. 1 - kerosene + air, 2 - H_2 + air, P =4905 N/m^2, T =2500°K, $\alpha_B = 1$, $K_F = 0.2$, $\varepsilon_T = 0.01$.

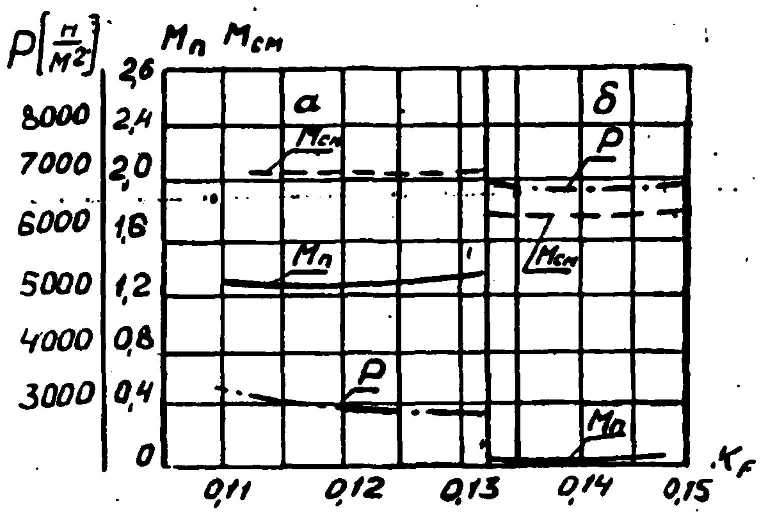

Fig. 8. Dependence of $M_п$, $M_{см}$ and P on K_F at 0.3 m from the intake. Kerosene + air, M_e=2, P_e=4905 N/m², T_e^*=2000°K, α_e=1.4, ε_T=0.007.

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